

RECENT R & D MODEL RESULTS ON AN IMPROVED SSC DIPOLE MAGNET\*

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### Introduction

Models of the 6.6T, 40 mm bore dipole magnet for the SSC have been built in 1-m and 4.5 m lengths<sup>(1,2)</sup>; recently, full length 17 m models have been built<sup>(3)</sup>. These models use a 3-wedge cross section and stainless steel collars. Recent R&D results at Lawrence Berkeley Laboratory aimed at improvements in current density and field uniformity are described; a 4-wedge cross section has been tested. Also, progress has been made toward elimination of magnet training and understanding of internal coil stresses.

### Superconductor and Cable

Improved NbTi alloy and multiple heat treatments have recently resulted in increased  $J_c$  of wire from production size billets.<sup>(4)</sup> In addition, the use of diffusion barriers to isolate NbTi from copper during extrusion and heat treatment has resulted in reliable production of 5  $\mu$ m filaments to minimize magnetization at low fields. Presently, 5  $\mu$ m filaments and a minimum  $J_c$  of 2750 A/mm<sup>2</sup> at 5T, 4.22 K, is specified for the SSC. Production wire with 5  $\mu$ m and 3400 A/mm<sup>2</sup> has been produced. Meanwhile, small lots with  $J_c$  up to 3700 A/mm<sup>2</sup> have been produced so there are good prospects for exceeding the present specification in future production.

Local damage to filaments often occurs as the cable passes through flattening collars during manufacture. This can easily reduce overall critical current by as much as 15%. However, with control of wire and cable parameters, we believe damage can be limited. Lengths of both inner 23-strand cable and outer 30-strand cable with

5-8  $\mu$ m filament diameter made recently at LBL have shown negligible degradation with cabling.

### Collar Design and Coil Prestress

The four coils are assembled with interlocking collars (similar in concept to those used in the Tevatron) that provide accurate coil positioning and prestress to minimize conductor motion. Prestress of at least 25 MPa is required for the inner layer and 20 MPa for the outer layer to maintain contact with the pole at 6.6T.

The present design uses self-supporting, 15 mm wide stainless steel collars fastened with two keys on each side as shown in Fig. 1.

Previous measurements on 1-m models<sup>(5)</sup> with stainless steel collars showed that the azimuthal prestress applied to the coils during collar assembly is reduced immediately by 50-60% as the assembly force is transferred to the keys and collars. This is due to assembly clearances and elastic deformation of the collar pack. Subsequently, further reduction of about 15 to 25% occurs due to creep of the plastic insulation during room temperature storage. Also, because of the relative thermal contraction of coils and collars, an additional loss of 28-36 MPa occurs during cooldown. This is illustrated in Fig. 2 from reference (3). If the collar pack is stiffened by welding along the edges to prevent relative rotation of adjacent collars, assembly "springback" is reduced to about 40% (Brookhaven National Laboratory results on spot-welded collars indicate similar results; however, on subsequent cooldown, the stiffer collar will result in a greater loss of stress than in the unwelded case. This additional loss was about 10 MPa in the single test made on edge welded collars.

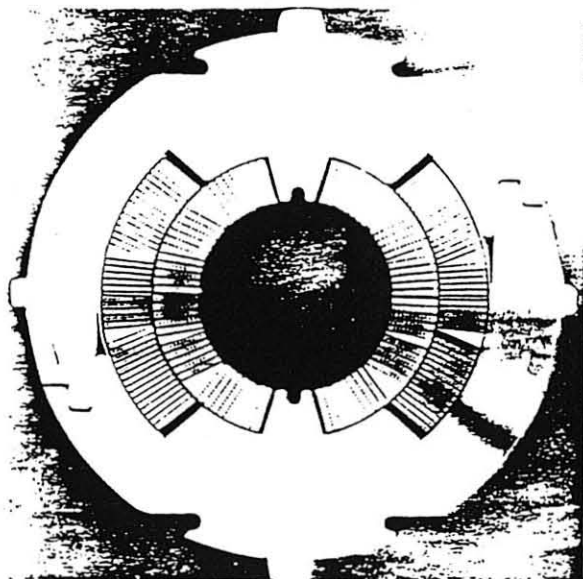


Fig. 1. Photograph of cross section showing a 4-wedge coil configuration.

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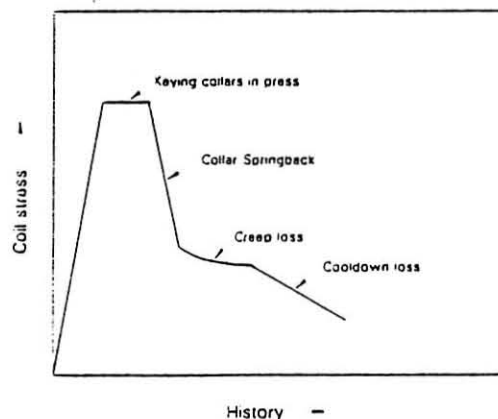


Fig. 2. Azimuthal stress in the windings during assembly and cooldown of magnet (not to scale).

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In contrast, aluminum collars lose less prestress on cooldown because of greater thermal contraction; also, they have lower cost. Recent measurements on two model magnets with 15 mm wide aluminum (7075 alloy) collars indicates that a prestress loss of about 14 MPa occurs during cooldown. Figure 3 shows the inner layer azimuthal stress vs. temperature during initial cooldown of magnet B-1 with Al collars. The room temperature and liquid helium temperature values are well established, but additional calibrations are required to accurately verify the exact shape of the curve; nevertheless, this general shape has been observed in several different magnets with Al collars.

However, the "springback" loss increases to about 60-70% because of the lower elastic modulus of aluminum. The result is that, for equivalent prestress when cold, the peak assembly stress is nearly equivalent for aluminum and stainless steel; however, while stored at room temperature the coil stress is about 20 MPa lower for aluminum, which should result in a lower creep rate. Three magnets constructed this way have been tested and behave as expected.

Figure 4 shows the azimuthal inner layer stress against the collar in magnet B-1 during an initial cycle to 3T and during a later cycle to 7.2T after the first conditioning cycle. The hysteresis may be due to friction between windings and collar. There is an upward shift in the zero-field stress and additional hysteresis when the magnet is first cycled to a higher field. After the cycle to 7.2T, repeated cycles to the same or lower field show that equilibrium has been achieved. This behavior has been observed in several magnets and the hysteresis may be related to the frictional heating that initiates training quenches.

At about 7T, the pressure against the pole in this magnet reached zero; this provides an independent check on the strain gage calibration. In the absence of friction, when the Lorentz force is removed, the pressure on the inner layer at the pole should increase by 28 MPa (4050 psi) which is consistent with the observations.

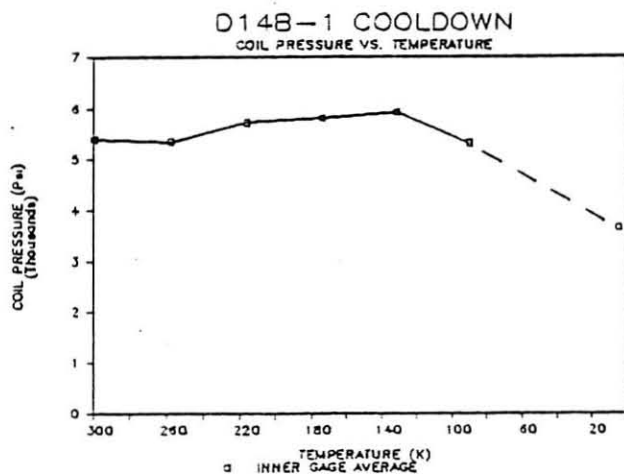


Fig. 3. Azimuthal pressure of the inner layer winding against the pole during initial cooldown of magnet B-1 with Al collars. (Average of gages in upper and lower halves.)

## Coil Cross Section

Early models used three wedge-shaped spacers in the windings to control field uniformity;<sup>(1,2)</sup> however, four wedges seem to be needed for sufficient field uniformity.<sup>(6)</sup> Fig. 1 shows one such cross section that has been used for the B-series model magnets at LBL; the calculated "allowed" multipoles are extremely small (less than a few parts in  $10^6$  at  $r=1$  cm). The measured multipoles at 7.0T in magnet B-2 are shown in Table I; these values meet the SSC uniformity requirements; however, we have not built enough models of this type to determine the magnet-to-magnet variations due to fabrication tolerances.

Lower stiffness of Al allows about three times greater deformation from magnetic forces than stainless steel. This deformation can be eliminated by allowing the collar to be supported by the iron yoke at the mid-plane. The three 1-m models with 15 mm wide Al collars that we have constructed and tested are supported in this manner and have operated satisfactorily.

The coil assembly was supported at two places at the mid-plane as shown in Fig. 5. Upon cooldown, the outer diameter of an Al free-standing collared coil would decrease about 0.2 mm relative to the inner diameter of the iron yoke; therefore, to maintain firm contact, the coil assembly is slightly deformed (elastically) during installation so that it returns to the desired shape when cold. If desired, this shim thickness can be selected for each magnet to control the mid-plane diameter of the coil and to adjust the coil position within the iron yoke to compensate for small sextupole and quadrupole field distortion that may have been accidentally built into the coil.

## Elimination of Training

Nearly all high current density accelerator magnets when first energized exhibit sudden transitions to the normal state at a current well below the design current; when cycled repeatedly,

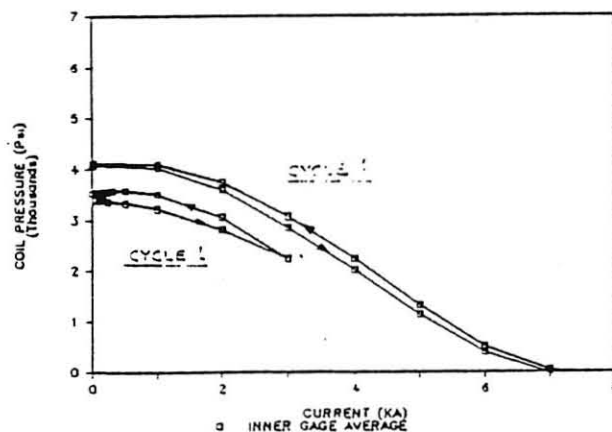


Fig. 4. Pressure of coil against pole as field increases (average of upper and lower inner layer).

the quench current reaches higher values on successive cycles until the critical current is reached. This "training" is generally retained throughout the life of the magnet unless it is disassembled.

In both 1-m LBL and 4.5 m BNL models of SSC dipoles, about 3-4 "training" quenches are required at 4.4 K to reach critical current. For the SSC with approximately 8000 dipoles, training each magnet with characteristics similar to these models would be costly.

Training is generally thought to be caused by sudden local releases of heat within the windings caused by surface friction as the Lorentz forces are applied to conductors which are not perfectly supported and can move slightly. Local temperature increase is caused by the small heat release and, if the critical temperature is reached, a quench occurs.

With successive cycles, the windings become "packed" into their equilibrium position by the Lorentz forces and the magnet will not "train" when subsequently operated at lower current.

A straightforward way to reduce training is to simply add enough copper to the conductor to insure that this heat is quickly conducted away to the liquid helium coolant, limiting the temperature rise so that no quench occurs; however, the resulting lower overall current density would not be acceptable for an economical SSC magnet. Therefore, we try to reduce the local friction heating by supporting the cable so movement is reduced, and reducing friction coefficient between sliding surfaces. These measures minimize but, unfortunately, do not eliminate training. However, by reducing the temperature well below the operating value the critical current density is greatly increased, heat releases from unavoidable movements

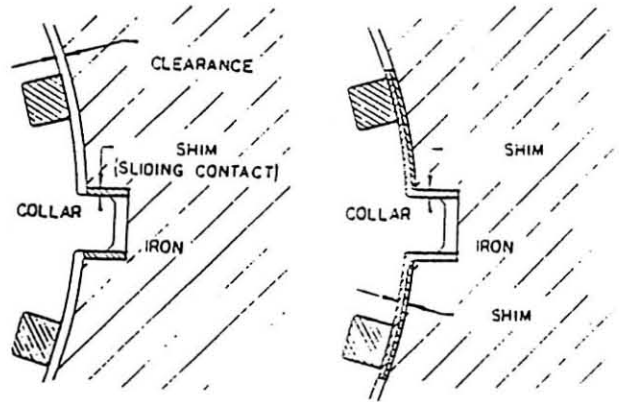


Fig. 5. Illustration of mid-plane support between collars and iron yoke used in models with 15 mm Al collars. Also shown is free-standing stainless steel collar in the same yoke.

can be tolerated, and the magnet can be operated to well above its operating field without quenching.

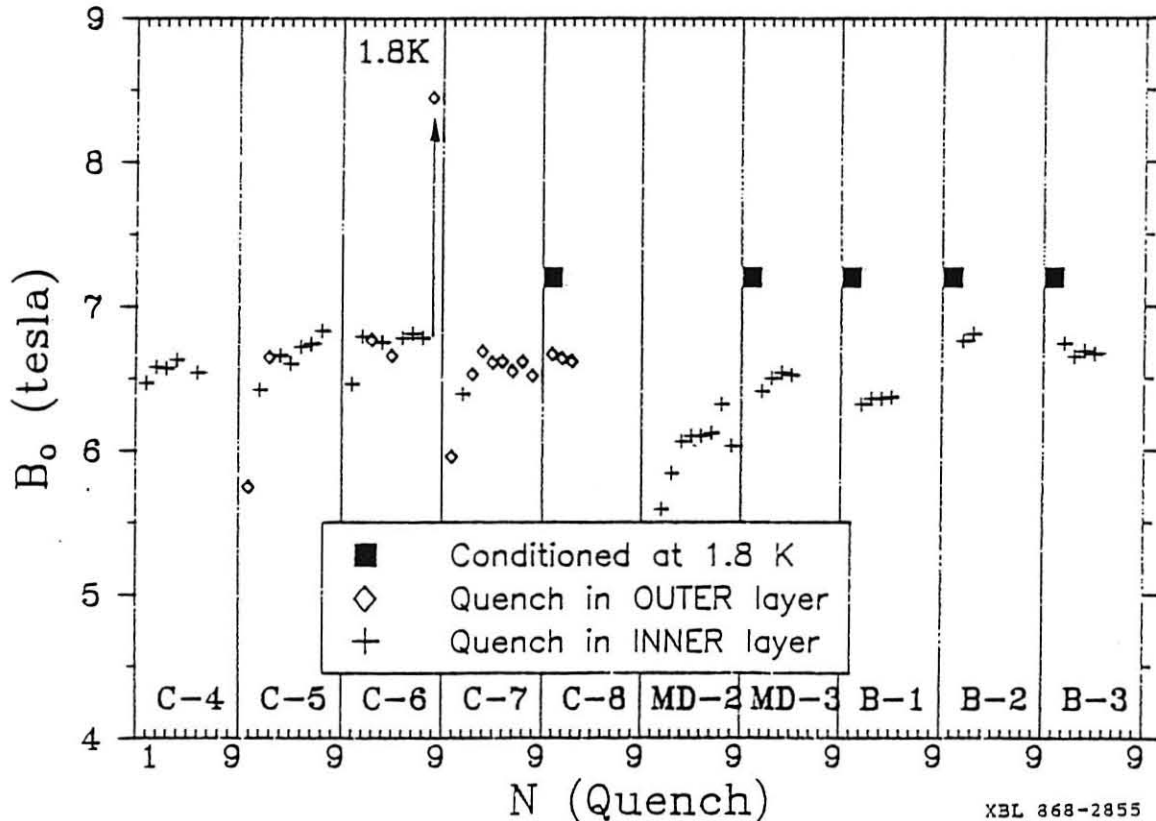


Fig. 6. Training history at 4.4 K of ten LBL 1-m SSC models. Cable with various critical current is used.

At LBL we have "conditioned" 1-m models by first operating briefly at 7.2T at a reduced temperature of about 2 K; no quenches occur during this operation. Subsequently the magnets operate at 4.4 K to very near the critical current limit without training. After cycling to room temperature, they again operated at 4.4 K without training. Fig. 6 shows the training history of the last ten models of which five were conditioned as described above; the five without conditioning had typical training quenches. For the SSC, magnets might be similarly "conditioned" either individually or by groups after installation.

Table I.  
Multipole Fields (mean of rising field  
and falling field measurement)  
LBL Model B14-2 (Al collars;  
NC-6 Cross Section)

	n	Measured by 7.0T		Specified Tolerances <sup>(7)</sup>	
		b <sub>n</sub>	a <sub>n</sub>	b <sub>n</sub>	a <sub>n</sub>
4-pole	1	-.06	.20	0.7	0.7
6-pole	2	.14	.45	2.0	0.6
8-pole	3	-.05	.18	0.3	0.7
10-pole	4	.41	.01	0.7	0.2
12-pole	5	.01	.02	0.1	0.2
14-pole	6	.04	.00	0.2	0.1
16-pole	7	-.01	.01	0.2	0.2
18-pole	8	.11	.00	0.1	0.1

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